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ABSTRACT

The Educational Technology Center (ETC) Complex Systems Project was initiated to explore ways of using computers to help students understand systems which have often proven too complex for most high school students to understand. Preliminary work concentrated on the cognitive processes involved in modeling simple systems. This paper describes an experiment involving an actual system of helium-filled balloons and a computer simulation of the same system with which students practiced changing equilibrium states and collected information about various aspects of the system that affected the equilibrium of the balloon. Researchers used observation and interview techniques to learn how the students perceived which elements in the system were critical to equilibrium. Included are: (1) experimental procedures; (2) a discussion of the student experiment; (3) transcripts of student problem solving; (4) a description of a computer simulation of the balloon problem; and (5) a discussion of experimental results. (CW)

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UNDERSTANDING EQUILIBRIUM:
THE STUDY OF COMPLEX SYSTEMS

Final Project Report

June 1985

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UNDERSTANDING EQUILIBRIUM
THE STUDY OF COMPLEX SYSTEMS

FINAL PROJECT REPORT

June 1985

Written by
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We gratefully acknowledge the cooperation, patience, and hard work of the high school students from Ware High School and Cambridge Rindge Latin High School who agreed to participate in this study.

Complex Systems

INTRODUCTION

The ETC Complex Systems Project was initiated in the fall of 1983 to explore ways of using computers to help students understand biological and physical systems which have heretofore proven too complex for most high school students to understand. After some initial exploration of the difficulties of teaching about such systems, project members were persuaded that before attacking extremely complex biological systems, we needed to get a better grip on the cognitive processes involved in modeling somewhat simpler systems.

In broad terms, we needed at least preliminary answers to the following questions: How do people begin to make sense of a system which has a number of variables? Do they build an understanding of each variable alone, as well as the relationships among the variables? What strategies help them in this endeavor? What questions or situations cause them to reconsider their assumptions in order to develop a more complex understanding of the system?

More specifically, we wanted to know how high school students come to understand equilibrium in such systems -- the state of a system in which no further net change is occurring. In understanding what this term actually means, an individual must have some concept of both the individual variables and the relationships between those variables which allow them to achieve a state of balance. Exploring the balance which is achieved by competing rates or forces leading to something not happening presents a perplexing problem to the learner. Rather than discover why something is occurring, s/he must determine why something is no longer occurring. Such thinking requires attention to both the individual forces and the relationships among them.

For purposes of exploration, we designed an experiment involving a system of helium-filled balloons. In our balloon experiment, the student was asked to change the height of one helium balloon (the "working balloon") to match the height of another (the "standard balloon") by clipping string off the working balloon or by adding any combination of strings and "helper balloons" to it. By adjusting the height of the balloon, the student was actually changing the equilibrium state of the balloon and beginning to collect information about the various aspects of the system that affect equilibrium. After students completed this task, the researchers uncovered, through observations and questions, how the students perceived which elements in the system were critical to equilibrium.

Below we describe the procedures followed in our exploratory research with the system of helium balloons and report the results.

METHODS

SAMPLE

The experiments were conducted with fourteen high school students, two from Cambridge Rindge Latin High School and twelve from Ware High School. Participant selection was based on age, availability, and an interest in participating in the study. Originally we intended to work exclusively with ninth grade students from Ware. We added the two Cambridge students when we had difficulty in Ware enlarging our sample within our age group. (For the record, the Cambridge students were not noticeably different from the Ware students in their understanding of the system.) We decided to include a group of twelfth graders when we found that the younger students were having difficulties with the subject matter. The twelve Ware students included five ninth grade males, five ninth grade females, and two twelfth grade females. The Cambridge students were ninth and tenth grade females who volunteered to meet with researchers after school.

PROCEDURES

The Ware students participated in the research in school time during their study period. Subjects were interviewed in small groupings of two, four, or six students as we were interested in understanding how students learned

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from or were hindered by one another - interactions more closely approaching a classroom setting. We later decided, however, to divide the two larger groupings into smaller sections in order to make it easier for the interviewers to follow the line of questioning of the individual subjects.

Subjects were interviewed for at least three and no more than five sessions at approximately weekly intervals. In-school interviews lasted approximately forty-five minutes each and after-school interviews lasted approximately one hour. Each interview was audiotaped, transcribed, and analyzed to determine the students' progression throughout the sessions and to discover any similarities among students.

HELIUM-FILLED BALLOONS

Two experiments were used, one involving helium-filled balloons, and one involving a computer simulation of the same. In the former experiment subjects were presented with several balloons. Of these, one "standard" balloon was weighted to a height of some three feet from the floor by several lengths of medium-weight twine. Three or four "worker" balloons were weighted to various heights less than three feet with finer twine. (This difference in string weight was used to rule out the possibility of counting the number of strings to address the initial question as numbers are often taken for answers by some students.) A similar number of "helper" balloons were let float to the ceiling, weighted only by a fine thread which

made them accessible. To begin the experiment, the subjects were asked to try to make one of the "worker" balloons level with the "standard" (fig.a).

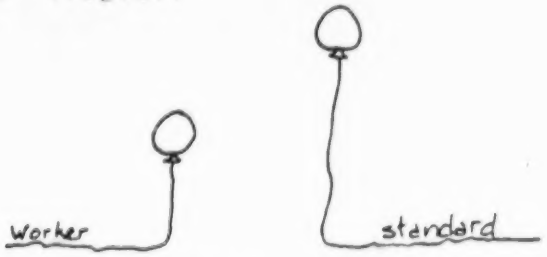

fig.a

In achieving this, subjects could adopt two basic strategies: either they could alter the weight the balloon had to lift by adding or cutting string or appending some other kind of weight such as adhesive tape, a paper-clip, etc., or they could attach a "helper" balloon to the "worker". Whichever strategy they adopted, the experimenter tried through questions to get the subject to verbalize what his/her thinking, in order to gain an insight into the subject's understanding of the phenomenon. In the following example the subject is considering the effect of a knot in the string to the balloon's height:

(The subject ties a knot in the string. The balloon falls noticeably.)

Experimenter: Why do you reckon it did that?

Subject: Well, because of the weight.

E: The weight?

S: When you put the knot, it has more weight.

E: So you're saying that the string is heavier with a knot

in it than it is when there is no knot in it?

S: Yes.

E: Some people would say that it's the same weight with or without a knot; it's the same string. Does that make sense to you?

S: Mmm. (pause) Maybe it's because the string's more... more... (hand gesture)

E: Compacted? Bunched together?

S: Yes.

E: That makes it heavier?

S: No, not heavier, but.... Like if you had paper instead of string, and one sheet was flat and the other was all bunched up. The one that was bunched up would come straight down, but the one that was flat would come down like this. (Gestures motion like a feather falling in air.) Because it has more resistance.

E: How do you mean "resistance"?

As the subjects became able to articulate their ideas of what was happening, the experimenter tried to ask questions which would lead the subjects to test these theories. As they did so, and as they continued to verbalize their thoughts, it was possible to trace the development of individual students' understanding of the phenomenon. Here the experimenter tries to help one subject explore and test his theory regarding the knot in the string:

E: How do you mean "resistance"?

S: It has more air pushing against it so it falls slower than the other one.

E: So what you're saying is that the knot in the string makes the balloon fall faster?

S: Yes.

E: Would it make it fall lower or just faster?

S: Mmmm. It would make it fall faster; I don't know about lower: we should try it.

E: Do you want to try it?

S: Yes.

(Subject begins experimenting with two balloons, one with a flat sheet of paper attached, one with crumpled paper of equal size. He makes several attempts reducing the size of each paper by half each time. Each time the balloon falls to the floor with no noticeable difference in speed.)

SIMULATION

In addition to experiments with real helium balloons, we introduced the students to early stages of a computer simulation of the balloon system to see if such a model made the understanding of the system any easier. Our interest in the simulation was to explore how the students' approach to the question differed between the real balloons and the computer simulation. By entering data regarding the size of the balloon, the number of strings attached, and the height

from the floor at which the balloon is released, the subject could see a representation of the behavior of a real balloon. To begin the experiment, the the subject was asked to try to get the balloon to stay level at the point at which it is released. (A question equivalent, we thought, to trying to get the worker balloon to float at a given level.) Using this as a starting point, the experimenter tried to follow the development of the subject's understanding in the manner outlined above.

Two versions of the simulation were used with all of the subjects. The first simulation was quantitative, in that the data were to be entered in numerical form: the diameter of the balloon and the height above the floor were requested in centimeters, and the number of strings in integers (or decimals, as the students soon discovered). A display then appeared in the form of a graph representing the behavior of a balloon of the given dimensions under the given circumstances, the x-axis representing the height of the balloon and the y-axis the time in equal units of unspecified length.

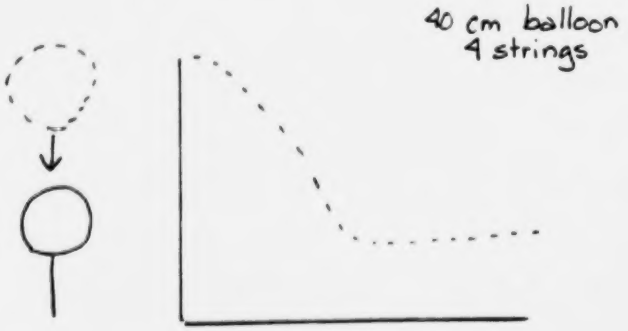

fig.b

After the data on the balloon were entered, the student could watch on the screen display (fig. b) as the balloon rose or fell over intervals of time. To the left of the graph described above appeared a visual representation of a balloon which varied in size according to the dimensions entered, and which rose or fell in time with the line on the graph. In the first version of this simulation, students had to press the space bar for each interval of time; in the later version, time intervals occurred automatically and could be stopped by touching the space bar.

Some members of the research group felt that this model focused more on a numerical manipulation than on understanding the factors contributing to the system, and a second, more qualitative simulation was designed. In the qualitative version, numbers and the graph were replaced by choices of small (S), medium (M), or large (L) for the size of the balloon and small (S), medium (M), or large (L) for the number of strings. The balloon could be released from one of three levels, namely the floor (1), the table (2), or the ceiling (3). The screen display showed a balloon of the selected diameter at either the bottom, the middle, or the top of the screen. As in the previous model, this balloon rose or fell according to the data entered.

Unfortunately this model had an unintentional flaw in the program which allowed the balloon to perform in inconsistent ways, i.e. a heavy balloon with heavy strings rose at the ceiling and floor height but fell from the table height. This

model was designed near the end of our study and we were unable to change the program. We were able, however, to observe how students reacted to a program that was clearly in error. For most students this version of the simulation was used less and appears to have been less interesting as evidenced by comments such as "This one is boring." When asked to explain why they found the qualitative version less interesting than the quantitative one, students explained that it was "too easy" which we assume is related to the limited number of the possible combinations. It did not seem to lead any more easily to an understanding of the phenomenon.

Although the opening interview question for the computer simulation ("Can you get the balloon to remain level when you release it?") was meant to be parallel to the opener with the real balloons ("Can you get this balloon to stay at the same height as that balloon?"), its effect was different and, we now judge, better. Students did not discuss the height of release when using the real balloons, unless they had first encountered it in the simulation. It turned out to be a perplexing question for many of the students, and we would now start an exploration with this question instead of the "worker" and "standard" balloon format.

RESULTS

We have chosen to describe in detail the three sessions with the two female twelfth grade students. They faced all the same difficulties encountered by the other students, and their means of resolving them shed the greatest light on the nature of the difficulties. Unlike the other students, however, Kim and Tina were able to reach their own conclusions about the balloon system based entirely on their own experimentation. For these reasons these students were not representative of the sample. Their case is presented because it shows best the fullest development of students' thinking while using the materials and, therefore, becomes a standard against which we can look at the other students' understanding. This case study also gives the reader an understanding of the specific problems common to all subjects.

FIRST MEETING

All three meetings with these students were held in a small office. A computer was set up with the two balloon simulations described earlier, and several helium balloons were placed in the middle of the room. The subjects were invited to use whichever of the materials they pleased. In each of the first two meetings they began with the computer simulation but turned to experiment with the real balloons after a few minutes. In the third session they used the real balloons exclusively.

Abstract

In this session, Kim and Ellen encounter the programming flaw in the computer simulation, but do not investigate it in depth. Turning to the real balloons, they are puzzled when the balloon rises all the way to the ceiling after what they took to be ineffectual string (the string lying on the floor) has been cut off. Kim hits on the idea that the weight "closer to the balloon" is "more important" than weight "far away from the balloon". She reaches this conclusion after investigating in particular the effects of tying a knot in the string which is attached to the balloon, and of transposing a length from the end of the string which is on the floor to the end which is tied to the balloon.

Narrative

Kim and Ellen begin with the computer. They choose the qualitative version of the simulation and enter: large balloon with large number of strings, released from the ceiling. Because of the flaw in the program (on which the researchers do not remark), the balloon rises through the ceiling. This does not seem to strike either of them as strange, and they try again to make the balloon go down. They enter the same details as above, except that they substitute a small balloon for the large one. Once again, this time to gasps of

surprise, the balloon rises through the ceiling!

"Why did it do that?" we ask.

"I don't know," says Kim. "I guess it depends on where it is.....Wait, I guess if it was down by the bottom there would be more gravity, right? So if it was up by the ceiling there would be less gravity."

How is that, again? Down by the floor there is more gravity?

"I don't know....It's an idea, right," she laughs.

They begin again, this time with a large balloon and a small number of strings, released from the floor. Ellen is not sure of what it will do. " It's going to go up. Maybe it won't go up."

It goes up.

"There", she says.

Is that what she thought it was going to do?

"Yep," she says.

They try releasing the balloon from the floor: even a small balloon with a small number of strings, to their surprise, goes up. "There must be more gravity on the floor", says Kim.

"But it's still going up,"says Ellen.

"Yes, but not much," says Kim.

Does this make sense?

"Not to me", says Ellen.

What would make it make sense?

Kim thinks for a bit, "I suppose.....", she begins, " if the string is more than the balloon it should go down, and if the string is less than the balloon it should go up. Because there's more helium pulling it up than there is string pulling it down.

Does she think that is what happens with the real balloons?

"I don't know," says Kim. "Let's try it."

The first time they experimented with the real balloons, Kim and Ellen were asked if they could bring a yellow balloon which was rested on its strings near floor level, to the height of a green one, which had been called the "standard" balloon and which was resting a little higher from the floor (see fig. 1).

fig.1

Kim suggested cutting the strings in order to make the yellow balloon rise. Ellen doubted at first that this would make any difference: if the balloon was to go up, she felt, more helium would have to be added. They agreed to try it, however, and Kim cut the string about two inches up from where it touched the floor (fig.2). To the surprise of both, the balloon rose all the way to the ceiling.

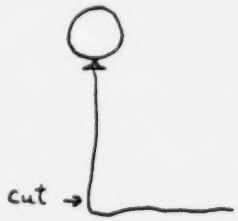

fig.2

After attaching more string to the balloon to bring it down again, Ellen notices that knots have formed around the

top. As Kim cuts them off, they notice that the balloon rises slightly. This causes them some puzzlement.

"I wonder," says Kim, "if the string closer to the balloon doesn't matter more to the balloon than the string at the bottom. We cut off tons from the bottom - the stuff that was lying on the floor....."

"..and it didn't matter," agrees Ellen.

They begin to think aloud, wondering whether it is possible that string which is nearer the balloon has a different effect than string further from it. An experiment forms in Kim's mind: would it be possible to take, say, five inches from the tail end of the string on one balloon and five inches from the top end of another and compare the effect on each balloon (fig.3)? Although even in working this out mentally it begins to strike her as somewhat absurd, she finds herself almost involuntarily engaged in the experiment.

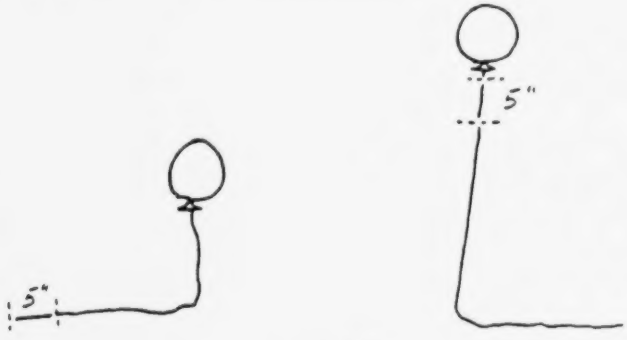

fig.3

While doing so, however, it occurs to her that it might be interesting to redesign the experiment. Instead of cutting the string from the top near the balloon, which would obviously free the balloon to float to the ceiling, what would happen if the

five inches cut from the bottom of the string were taped into place at the top (fig. 4)? She does this and is delighted to see the balloon fall a few inches.

"Hey! All right! So we've figured something out! We've figured out that the weight near the balloon is more important than the weight.....you know, far away from the balloon."

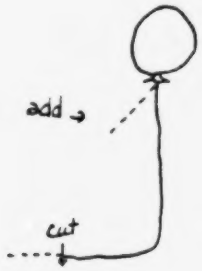

fig. 4

Kim deduces that the balloon can always hold a certain amount of string; it simply rises or falls until it is holding that amount of string. This much is congruent with her findings so far. But what would happen if the two balloons of fig. 4 were suspended so that their strings did not touch the ground? Since the balloon is already holding <u>all</u> of the string, would it rise if any were cut from the end and added close to the balloon? It seems to her that it need not, since it would already be holding its quota of string, and the amount of that quota does not change. In other words, therefore, her hypothesis is that if the balloon is holding its maximum quota of string, then its position will be constant as long as that quota is constant, regardless of the arrangement of the string. She does not test this hypothesis.

If this is true, however, then it should hold good also for

balloons whose string extends along the floor. She feels that it would not, and decides to try the following experiment. A balloon is floating three feet above the floor. The string to which it is tethered extends for approximately two feet along the floor. Since the balloon has adjusted until it is holding its quota of string (the suspended string), then it should not move if the string which is not suspended, and therefore does not form part of the quota, is cut off (fig. 5).

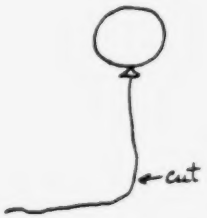

fig. 5

She remembers the first experiment above, where the balloon rose when the string was cut, and feels that it is likely to do the same this time. She cuts the string at X, just above floor level, and the balloon rises to the ceiling.

This puzzles her greatly. Why should the balloon move when string which it was apparently not supporting was cut off? "..That doesn't make sense.....it's really strange...." She thinks for a while and then muses, "It's sort of like when you cut someone's hair who had long hair and it curls .....and then it goes straight.....I'm never going to look at a helium balloon the same again!"

During the lull which follows, we ask Kim and Ellen what would happen if we raise the balloon and string at figure 6 to a postion above the table top.

"It'll go down", they both predict.

We move the string from the floor to the table top and release the balloon, which rises to the same distance from the table top as it had been from the floor (fig. 7). Their surprise is audible.

"It has to do with something..... It has to do with what's underneath it," begins Ellen. "Once it drops off the edge, it'll go down."

"Yes," Kim continues, "because the desk is holding it up."

And at that the bell sounds for the end of the period.

fig. 6

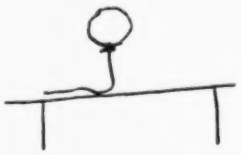

fig. 7

Remarks

At the end of this first session Kim feels that the weight of the string is an important factor in determining where the balloon comes to rest, but is also entertaining the erroneous idea that the position of the weight with regard to the balloon is also important. To her, this is substantiated by two apparent phenomena. Firstly the balloon did not rise when string which was at the end of the length on the floor ("far from the balloon"), and which the balloon was clearly not supporting, is cut off. It did rise, however, when the string was cut just at the point where it touches the floor ("closer to the balloon"). Secondly,

the balloon rises when knots ("close to the balloon") are cut off. This appears to Kim to demonstrate the balloon's sensitivity to weight which is closer to it.

At the end of the session she and Ellen both have the idea that the height of the balloon is influenced by height of the surface on which it is resting. Also worthy of mention is that both entertain the idea that it is possible for a balloon to hover without its strings touching the ground.

SECOND MEETING

Abstract

Although Ellen is not available for subsequent meetings, Tina comes along in her place. After only a few minutes on the computer, they choose to work with the real balloons. Kim introduces Tina to her idea of the importance of the proximity of the weight to the balloon, and they go on to investigate it together. In particular they investigate the properties of knots in the string, and explore the relative influence of length as opposed to weight.

Narrative

They sit down at the computer and begin to play with figures in the quantitative version as they wait for the session to begin.

We pose a question: what do they think would happen to a balloon 50 centimeters in diameter, with 50 strings, released at

50 centimeters from the floor?

"I don't know", Kim begins. "It doesn't say how long the strings are..... It'll probably go up."

They enter the data. The balloon falls.

Did that surprise them?

"No", says Kim. There was not enough data to make a prediction.

Did they think the balloon would always find a "balancing point" no matter what size it was./

"Yes", says Kim. And then after a pause, "The real balloons are more fun."

When they turn to the real balloons, Kim takes up where the last meeting left off. "Tina", she asks, "if I lift this balloon with its string from the floor on to the table, will it go down to the height it was at, or will it come up to this height?" And she shows with her hands a position above the table at a similar distance to the original position which the balloon held above the floor. Without waiting for Tina's answer, she releases the balloon above the table and it floats upward to its new position. Tina is surprised: Kim is pleased.

A teacher who happens to pass through our working area at this point has become intrigued. "Ah", she says, "so it'll always stay the same distance from whatever the strings are like - because of the weight of the strings.

"Yes", Kim and Tina confirm.

So, what will happen to the balloon if a knot is tied in the string.

"It'll go down," says Kim.

Why?

"Because the weight will be closer to the balloon."

We ask what effect tying a knot further down the string will have.

"It'll go down, but not as much," says Kim.

And if the knot is tied in the string which is lying on the floor?

"Nothing," says Kim. "That doesn't matter. It's just dead weight."

"But when you tie it further up the string, on the part that's hanging," adds Tina, "you're increasing the weight."

"Yes," Kim continues, "you're pulling so much string off the ground into the air."

Are they sure about that, we ask?

"Of course not!" laughs Tina.

Some people say that it is not the weight that counts. They say it has to do with the length of the string. Does that make sense?

"The length?" says Kim. "What difference does that make? It's still going to go to the ground."

"But," begins Tina, "it seems like by making the knot, you're increasing the length of the string between the balloon and the ground, and you're also increasing the weight."

So does that mean that what some people say does not make sense?

"No, no," explains Tina. "We're basically saying the same

thing. By making the knot, you're increasing the length between the floor and the balloon..... You're making more string between the floor and the balloon....Because you're taking up..... the knot. And you're actually taking more in length - you're making it weigh more."

We suggest an experiment. If we take a balloon with a string which just touches the floor and mark the point of contact between the floor and the string, then according to Tina's theory, that marker will rise when we tie a knot thus increasing the length. We tie the knot and no change takes place with the marker, but the balloon moves lower.

"Ah," she says. "No." She pauses. "You see, I thought that what you had been doing was picking up the string from the floor and tying a knot and therefore getting more string.... I didn't realize you were..... So it wouldn't weigh more."

Kim meanwhile is still puzzling over it. "....It's (the balloon's) going down because the length of the string is shorter but it still weighs the same amount. So if the length of the string got shorter by cutting it off, then it would weigh less and go up. But now the string is getting shorter which is pulling it down, you know. And it can't pull back up because it still weighs the same."

It would appear at this point that Kim has understood the relationship between the length/weight of the string and the height of the balloon; but, in fact, she does not as seen by the following comments.

So does that still fit with what she had said originally?

"I don't remember!" she laughs.

"Is there any way," asks Tina, indicating a point near the top of the string, "to make a knot up here so that the length of the string between the balloon and the ground is increased?"

"Hm. I just don't know how to do it," says Kim.

We admit that we don't know either. Finally we suggest taking the end of the string which is on the floor and attaching it to the string which is hanging (fig. 8). What did they reckon would happen?

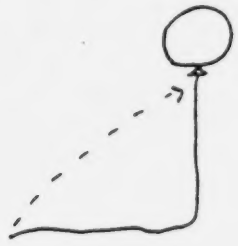

fig. 8

They predict that it would fall, try it, and find themselves proved right: the balloon falls measurably. "So it did work," says Tina. "If you increase the length.....the weight....., it goes down."

With that they turn their attention to another balloon whose string is just touching the floor.

"What if we tied a knot in the string," begins Tina, "so that it still weighed the same....just to see if it would come back to this height above the ground or if it would go down. I mean, if the string is shorter, I think it'll just stay at the same height.."

"Without the string touching the ground," Kim finishes for her.

"Right."

Why should it do that, we ask?

"Because it weighs the same," answers Kim.

They tie a knot in the string of the balloon, which falls until the end is once again just touching the floor. Kim and Tina are both surprised at this.

Why did they think the balloon would stay at the same height?

"Because it would have the same amount of weight..... But now the weight is closer to the balloon."

And what difference did that make?

"The balloon is lower," says Kim. And then she laughs, "That was just a guess for why it would be low."

Taking two balloons whose strings barely touch the floor, they speculate on what would happen if the ends of the strings were attached to one another. They think that both balloons would stay even, as they are at present, but would drop slightly because even though there is more helium, there is also more string.

And what if the strings were attached not at the ends but near the top?

"Good question," says Kim.

"The weight's closer to the balloon.....," says Tina.

What about that theory, we ask?

"..It has never felt true," says Tina, immediately.

But would the theory predict that the balloons would go down if their strings were attached to each other at the top (fig. 9)? They agree that it would: not all the way to the floor, but certainly a few inches lower. They tie the strings of the two balloons together near the top and watch what happens.

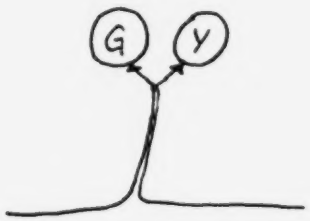

fig. 9

"It did go down slightly more," observes Kim. "But it's funny," she adds, "because the string always seems to touch the floor."

Why did she think that was? She wasn't sure.

It is important to note here that this is the first time that either of them appears to puzzle over the fact that the string is always touching the floor.

We turn to another experiment. What if we were to tie the "dead" end of the string of a green balloon (i.e. the end of the string which is lying along the floor) to the top of the string of a yellow balloon (fig. 10)? What did they think would happen?

"I think," says Kim, "the yellow balloon will go right down to the ground and the green balloon will go back to where it was (fig. 11)."

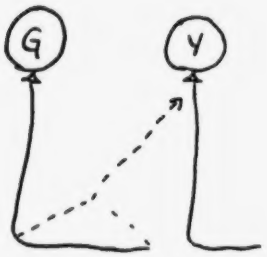

fig. 10

fig. 11 (Kim's prediction)

They tie the strings together as planned, and release the balloons. (fig. 12)

fig. 12

"See?" says Kim. "The green balloon's about the same height as it was, holding up the same amount of weight, and the yellow balloon's half as high because it's holding up..like...a double thickness, plus a knot."

"What if you taped the strings together instead of knotting them," says Tina. "There would be the same amount of weight, but you wouldn't get a knot. So there wouldn't be extra weight close to the balloon. Do you see what I mean?"

"Yes," Kim acknowledges.

So removing the knot meant removing an extra weight. Is that what they were thinking?

"I don't know," says Tina.

They think for a bit, and conclude that the green balloon will remain unaffected by the change, while the yellow balloon will again fall to half the height. Then they try it.

"Looks about half the height to me," says Kim, comparing the balloons.

"Looks about half the height to me, too," says Tina.

Kim thinks aloud. "They're both holding up the same amount of string, right? Same amount they've always held up. This green one is holding up that amount of string, which is about the same as it's always held up - a little bit more than the height of that chair. This yellow one is holding up the same amount as it's always held up because it's about half as high and is holding twice the number of strings. So it kind of seems like they can both hold up the same amount of string, you know.."

"But why did that other knot a while ago make it go down?" asked Tina.

"Because it was holding up more string," concluded Kim.

"But if we take a single balloon with the same amount of string, just touching the ground, and use that string to tie a knot..." mused Tina.

"Oh, wait a minute, you're talking about something different." interrupted Kim.

At this point, they leave their knot question and decide to test their hypothesis that the balloon can always hold up the same amount of string. They take a balloon whose string just touches the floor. They fold the string in half and predict that the balloon will fall to half its original height, allowing the string to touch the floor once again. It does just that.

"Hot Dog! I'm good!" says Kim.

"Let's fold the string in half again and see if the balloon goes down by half again," says Tina. "I think it will."

They do this and are pleased to see the balloon fall as predicted.

Again, it is important to note that they do not return to the observation that puzzled Kim earlier - why does the string always touch the floor.

"What if we tied the string on to the balloon?" says Kim, and she begins to fold the string into a compact pad, which she then tapes to the side of the balloon. When she releases it, the balloon falls to the floor, resting on the pad of string (fig.13).

fig. 13

What did they think that this experiment showed?

"It shows," begins Kim, "that it always goes to the end of the string."

"As long," adds Tina, "as it has enough weight. Because I mean, if it was just one string that long it wouldn't go to the end of the string.

Remarks

In this session two ideas from the previous session - the height of the surface is instrumental in determining the position of the balloon and the importance of the position of

the weight to the balloon - become starting points for the inquiry. They then move into an investigation and eventual agreement that it is the weight of the string which is important. Although their exploration of this concept leads them to the discovery that the balloon is always able to sustain the same amount of string, they appear reluctant to give up the idea that the closeness of this weight to the balloon is somehow important.

Kim's closing remark that the balloon always goes to the end of the string is ambiguous. It is likely that she was remarking on a specific detail of the experiment which she had just carried out rather than consciously generalizing to all cases.

THIRD MEETING

Abstract

In this meeting Kim and Tina wrestle with the concepts of weight, height, and thickness, and how they affect the behavior of the balloon. They come to the notion of balance and explore it using Tina's image of a seesaw.

Narrative

At the beginning of the third session Tina is still thinking about the notions of weight and length. Thinking aloud, she says, "If the string is twice as thick, the balloon will be half as high, though it'll still touch the ground. If it was three

times as thick, the balloon would be a third as high, and it would still touch the ground. Maybe the height is.....a function of..... the thickness of the string. Not the weight, because it's the same. It's the thickness."

She puzzles for some time over the notion of thickness. "I don't know," she goes on. "It can't be just the thickness, because you could get something that really.... I think it's like...if you play on a seesaw, if you have the same weight on both sides, it's fun. But if one person is really heavy it's not as much fun because they go all the way down. But if they sit closer in, then they balance it.... You know what I'm saying? It's that idea of balance...

What did she mean when she says "balance"?

"The balance," she answers, "is the helium going up and the string coming down.... I guess the balance is the point where the balloon stops, where it's no longer moving."

At this point another teacher enters and Tina begins to explain her theory: "This balloon will go to this height and the string will touch the ground. And you would think that with the same amount of string it would always stay at that height? But it doesn't. If you fold the string back on itself, the balloon will still fall so that the string touches the ground."

"So what have you learned from that?" asks the teacher.

"Well, that's what we're trying to figure out," says Tina.

"What is the one thing you have just changed?" asks the teacher.

"The length of the string... But that's <u>not</u> the one thing

that's changed, because also the weight is closer to the balloon," Tina points out.

"Oh, all right," says the teacher, "so maybe there's more."

"Maybe the thickness of the string," Kim suggests.

"But, see," says Tina, "that's not really important; it's not the thickness of the string..."

Did the computer help with this problem?

"No," says Kim, definitely. "On the computer it takes forever. All I wanted to do on it was.... I figured if I put one string on the balloon and I figured out where it stopped, then I put two strings on the same balloon and see if it stopped, you know, at half the height...But it was waste of time to know where it was going to stop, because it kept going down and down."

They turn back to the balloons.

"Our question is:" says Tina, " the height, of course, is affected by the weight of the string...but we are trying to figure out what else influences the height."

We pose another question. If we double the number of strings on the balloon, the balloon falls. They agreed. And if we fold up the string attached to a balloon, it also falls. Again they agreed. Were the two instances of the balloon's falling the same?

"Yes," begins Tina. "I mean it does the same thing, but not for the same reason..... Well, maybe for the same reason."

"Will it make any difference?" asks Kim. "Because now the string is half as long and twice as thick, right? It would be like just using two strings and folding them."

"Hm, that's right," agrees Tina.

Kim suggests that an equation might be found which expresses the behavior of the balloon. Thinking aloud, she begins, "Double the weight and you get half the height, right? Not double the weight, but double the thickness of the string, you know? Like, the heaviness of the string. Then you get half the height. So, like if you had a string that was a foot long and it rests on the ground, and it was an inch in diameter, and you had a string that was two inches in diameter, or whatever, you know, it would be half the height....."

So what was her question?

"If you take a balloon with four strings just touching the ground, and you take off two and attach them to the end of the other two, then the balloon would go up."

Interesting. What did Kim think of this idea: some people had tried to make a balloon go up by a certain number of inches by adding that number of inches to the end of the string. But nothing happened. Did that seem to make sense?

"Of course nothing would happen if it was already sitting on the ground," says Kim. "All they did was to add dead weight to the end of the string."

Although they are uncertain in stating their knowledge here, they are aware that they have understood something that the other students have not yet grasped about the relationship of the string to the balloon.

So how was what the other students did different from what Kim and Tina had suggested?

"Well," says Kim. "They didn't cut off any string: it was the same thickness. They just added on to the bottom. See, we're making the string thinner; they didn't change anything, they just added on extra weight."

"See," adds Tina, "if you cut off two of these strings, the balloon will have less pulling against it, so it will rise. And to add it to something that's buoyed up will be different than just to add it to the end of something that's already at its resting point..... It's hard to explain."

Kim puts in, "They just didn't know how to go about it." And everybody laughs. "Well, we figured out a long time ago that if you cut off a string that's lying on the ground it wouldn't make any difference, right? It would just stay touching the ground. And they - the people you were talking about - they were just taping it back on and expecting it to go up..... which it wouldn't."

Another idea comes to them. Kim takes a balloon which rests on its string some three feet from the floor.

"What if we attached another balloon to this one?" she wonders. "It's just like widening one balloon.....we attach one on."

We wonder if at this point she is refering to the computer model's way of adding helium by selecting a larger balloon as the manner in which helium is added to the real balloons is by adding a helper.

Measuring the height of the first balloon from the floor before they do so, they attach the second balloon, which is of a similar size, near the top of the string. As they release the balloons, they note. "It went up.....but not quite as high as before (fig. 14)."

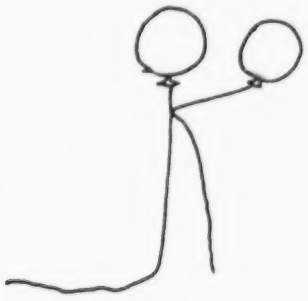

fig. 14

In the above experiment, the "helper" balloon had a string which allowed it to rest at approximately the same height as the first balloon. In the process of separating the two balloons they cut off approximately two inches of string.

What if we joined the balloons nearer the bottom of their strings? What would happen then? Should that make any difference?

"I think so," says Tina. "I don't know, but I think it should."

"I don't know either," ponders Kim.

The balloons are joined near the bottom of their strings (minus the two inches). As they are released they rise.

"That makes sense," says Kim. "Because you're making it twice as buoyant ....you know, twice as much helium, and this weight of string isn't going to make much difference."

Next they plan to have the same length of string lying along the floor as is susupended from the balloon itself but in doing so, hit on a new idea. Why not join another balloon to the "dead" end of the string (fig. 15)? They are not sure what the outcome of this might be, so we present a hypothesis to them. Might the balloons rise to a level such that the string touches the floor in the shape of a "V"? Yes, they think that would be possible. The balloons are released and the "V" shape forms.

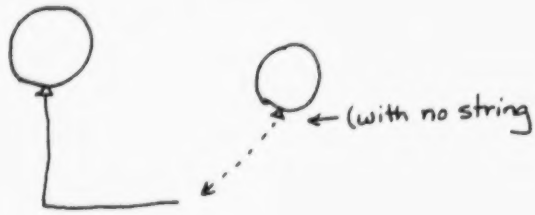

fig. 15

Tina thinks aloud. "That's the same amount of string that they could both hold up, connected in the middle. Each one singly would do the same thing if you cut it here in the middle."

So what, we ask, might happen to the "V" if we cut off about two inches of string and then reattached the balloons? Would they still form a "V" shape? And if so, where? At the floor? In mid-air? At the ceiling?

"It would make sense if they go all the way to the ceiling," says Kim. "Because they each have less string to hold them to the ground. So if they don't go to the ground they might just go all the way up."

They adjust the string and the balloons, and they rise all the way to the ceiling amid surprise and delight. "I"m glad they

didn't touch the floor," says Tina. "That would have been dumb!"

Did they think it was possible to get the balloon to hover in mid-air?

"No," says Kim. "It has something to do with the nature of helium. Helium is just going to go up unless you have enough gravity to make it come down."

Did the image of the seesaw help?

"I don't know," she says. "You can hover on a seesaw."

Tina agrees. "Yes, you can move right in to a point where you can balance."

Isn't that possible with the balloons?

Tina thinks. "Yes. OK," she says. "So you have the balance and then after you get out of balance.....it's just... you're never going to stay with one person up and one person down and not touching the ground. Once you've upset your balance - even a little bit - you're going to go down all the way."

"Good point," says Kim.

This is the first time that Kim and Tina comment on the difference between a self-regulating system and a non-regulating system. They appear genuinely sad that the study is ending. Kim explains:

"This was cool. I wish this wasn't the last time."

Remarks

Although they leave the relationship of weight, height, and thickness of string largely unresolved, Kim and Tina seem

to have arrived at a good understanding of the nature of equilibrium in the case of the balloon. It might have been useful to explore further what balance means in a self-regulating system, such as the balloon, and how much variance the system can allow before it is out of balance. To this end, a continued exploration of the differences between the balloon "hovering" with its string touching the floor, the balloon hovering "free" and the seesaw would have been important. Unfortunately time ran out and this question remained unasked.

REMAINING SUBJECTS

Although the younger students were often surprised by the balloon system and worked hard to understand what was happening, they were unable to create a complete picture of the system. Rather than reviewing their protocols, we will discuss the categories of inquiry which were common to many: general struggles with the original task, specific theories about knots, predictions about balloon behavior above various surfaces and interpretations of the effects of cutting the string. In some cases the students reached an explanation that was satisfactory to themselves and in other cases they did not. In all cases, however, we were able to explore with the students the ways in which they approached the problem.

INITIAL TASK

All students were able to complete the initial task of changing the equilibrium height of one balloon within a short period of time, usually ten to fifteen minutes. This task was designed to gave them enough familiarity with the system that they were willing to make predictions about what the balloon would do in various other situations. It succeeded in doing this. One of the more perplexing problems for all of the students was why the balloon rose to the ceiling when the string was cut at the point where it was no longer suspended and was lying inert on the floor.

We asked Philip and Steve if there was a difference in the string on the floor and the string hanging down.

"Yes," explained Philip. "The stuff that hangs down pulls it down; the stuff on the floor just lies there."

"Once you cut past a certain point, it goes higher," offered Steve.

And where is that certain point?

"Here where it still touches the floor," replies Philip and he cuts the string at that location. The balloon does not change height.

"Well, if you cut any more off, it will go up," predicts Steve.

What if you cut off just a little bit more?

"Maybe it would go up just a little," Philip offers.

Unfortunately, the balloon rose several feet from the floor and then dropped back down. This phenomenon, which occured with all of the balloons that day, was a result either of temperature differences in the room, or of inferior balloons which permitted a considerable amount of helium to be released through the rubber. This technical difficulty was an unfortunate part of the experiment as it raised questions about the construction of balloons, air currents, or the effect of heat on the system, none of which we were interested in pursuing. It was a reality which complicated the experiment at certain points by giving the students confusing data.

Philip and Steve went on that day to develop a theory

about the system which included a balloon which could hover without the string touching the ground. Philip explains:

"(When the string is cut,) the helium is strong enough to pull the balloon up, but the weight pulls it back down."

"Yeah." Steve agrees. "Because it lost some weight when you cut the string, so it went up, and then it just...balanced out."

The interpretation of the time dimension here is noteworthy: one factor pertains and then the other.

These students go on to explain the dynamic relationship that they see between the "forces" of the balloon system, which they identify as the helium and gravity. Although they are never able to explain what gravity is, they continue for the next several sessions to attempt to make the balloon hover without touching the ground, a task which they are never able to complete. They attribute the failure to their own inability to "cut just the right amount of string." Their inquiry throughout the sessions focused solely on this question of the relationship between helium and gravity. Although they certainly were addressing, at least in part, one of the difficult questions, they were attempting their exploration without fully understanding what factors were operating in the balloon system. Rarely in their conversations did they discuss the string itself, only gravity.

The reliance on a word, usually "gravity", that may have been remembered from science class but never fully understood, was also seen in other students. In most of these instances, we noted that the students did not actually use the word until they were stuck and could no longer explain the situation through the system itself. In these cases the students almost seemed to be giving up on trying to find an explanation. Rather than doing more experiments or re-examining what they had already done, they left the system behind. In some ways they had grabbed onto something that enabled them to stop looking for an answer.

For example, when Billy-Jo, Carol, and Pete were exploring why the balloon went up from the floor and down from the ceiling, the idea of gravity almost stopped the inquiry. Billy-Jo began struggling with why the balloon went down from the ceiling; Carol offered gravity as an explanation. When asked why gravity didn't seem to affect the balloon when it was released from the floor, Carol responded:

"You got me. Well, cause the ceiling is far up."

So the gravity only works far up?

"Well, it works more from far up." Carol explained.

Could she talk more about how gravity worked?

"No, not really"

"Me neither!" laughed Pete, who had previously used gravity as an explanation for this situation.

Billy-Jo stressed that she had never understood gravity anyway and that it certainly wouldn't help her understand this

system; she continued to explore the balloon's behavior.

ANALOGOUS IMAGES

Another strategy used by a number of students was to think of images with which they were familiar. Unfortunately, these images were not always as helpful as Kim's seesaw image and in one instance the student's example seemed to actually impede her understanding and further exploration. Sally was convinced that the balloon system was analagous to a boat and anchor. She explained to her fellow students that the extra string which rests on the floor fulfilled the same function that an anchor provides to a boat and without it the balloon would go to the ceiling, just as a boat would float away without an anchor. Frank was not as convinced of this theory; he believed that a knot in the string, which they had already seen bring the balloon closer to the floor, had more effect than the "anchor". To test out which theory was correct, they decided to tie a knot just above the point where the string touched the floor.

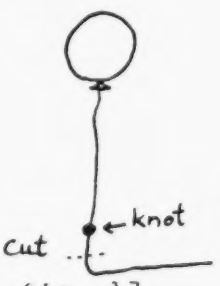

fig. 17

Although the purpose of this experiment was to see which idea was correct, both believed that the balloon would not

rise when the string was cut just below the knot; both were genuinely surprised when it rose to the ceiling.

"Well," observed a third student, Peggy. "I guess that the anchor theory is right then!"

This "evidence" for the validity of the anchor theory, predominates all of the remaining sessions as these students continued to rely on this image. For example, when the string is cut so that it hangs down from the balloon and just barely touches the ground, the explanation is that "there is still a little bit of anchor there." When the string is cut just above the ground and the balloon rises to the ceiling then eventually begins to drift downward, the anchor image again provides the explanation in different ways to two different students:

"The reason that it floats around the room is because it doesn't have anything to attach on to." Peggy explains. "It came down because it needs something to grab hold of."

Sally is skeptical.

"Yeah, it sat up there looking around, right?"

Sally never accepts this interpretation of her anchor theory since she believes that it should go up and stay up because "it had no more anchorage". She can offer no alternatives to Peggy and in the end each girl is convinced that her interpretation of the meaning of the anchor is correct. Their strong belief in the initial evidence that they found to support this image actually prevents them from exploring other explanations. Although the theory is

inadequate to explain other aspects of the balloon, both girls continue to use it and seem to ignore its inadequacies.

Like Kim and Tina, some of the other students were able to work out some problems to their satisfaction. Billy-Jo had explored balloons for two sessions before she uncovered what for her became a perplexing problem. After working with the computer she began to wonder why the balloons went up from the floor and down from the ceiling. She repeatedly stated that it "makes no sense" and wasn't "logical". She believed that it should keep going up wherever it was released or keep going down wherever it was released. As mentioned above, Pete and Carol had offered gravity as an explanation for this phenomenon, but neither could explain to Billy-Jo how gravity helped explain this particular "illogical" occurence. After over fifteen minutes of releasing the same balloon from the floor and then from the ceiling, the students remained stumped.

Finally, Pete tried releasing it from waist height (about the height where the balloon was resting) and it stayed at the same place. Billy-Jo suggested that he repeat that action and lift up all the string before releasing the balloon. When it remained at waist height, Billy-Jo concluded that "it can't go up any higher than right there with the string. It will go up the same amount as it did from the floor." Pete thought this was "weird" and proceeded to hold it down by the floor and released it again. Billy-Jo prediction that it would "go right

back" to the waist high spot was correct.

"The helium and string kind of go together so it stays right there at that point," she concluded. " So if you let it go from somewhere else it will go right back to that point."

KNOTS

All students were especially intrigued by some one element of the balloon system and often spent most of their time examining that phenomenon. For many students, knots represented the ultimate challenge in logic. No one was surprised that the balloon went down because of the knot and all explained it by saying that a string knotted weighs more than the same amount of string un-knotted. When confronted with why a knotted string would weigh more than the same string unknotted, they came up with a number of solutions. In an example mentioned earlier, Pete becomes stumped when the researcher reported that some people say that the string would remain the same weight with or without the knot. He then proceeds to ignore that logic entirely and move to an explanation which involves mass rather than weight. When the researcher asks if the mass theory explains why the balloon goes lower with the knot, the student is once again stumped. "Mmmmm, it would make it fall faster; I don't know about lower. We should try it."

Subsequent experiments offer no proof for the faster theory nor insights into the reasons for the balloon going

down when a knot is tied in the string, and the student leaves without a resolution to his initial question.

Holly and Jessica explored the significance of knots to the system in a different way. We asked what they thought would happen if we tied a knot in a balloon that had its string off the ground.

" It would go down lower because the string would have to touch the ground." Holly insisted.

Jessica disagreed and stated that she didn't think anything would happen.

"See, nothing happened." stated Jessica after the knot had been tied, "Well, something happened but it was only that the string is higher off the ground."

Holly disagreed. She thought that the change was a perceptual one in which the knot only looked higher than it had been before, but really it was the same.

When asked what would happen if a knot was tied in the active part of the string of another balloon with its string touching the ground, Jessica thought that the string wouldn't go up and the balloon wouldn't go down. Although Holly initially thought that nothing would happen because of "so much on the bottom", she eventually decided that the balloon would go down. After her prediction proved correct she offered the following explanation for her theory.

"That balloon (pointing to the balloon with string off the ground) is stuck on the ceiling... it is against the ceiling.

There is pressure on it of the ceiling so it's not going to go up any."

She goes on to explain that the helper balloon attached to the balloon with the strings in the air works against "the weight of the strings." When asked if the string got heavier with the knot, the students explained that it got "more concentrated" and that " the knot made the string less". Although these students did not seem to believe that the knot made the string heavier, they, like Pete, focused on the concentration of the string but unlike Pete they saw it in relation to some effect on the string, not the balloon. It is interesting that they did not seem to see the simple explanation that the knot shortened the string and explained it in more complicated language. This would have been a good point in their inquiry to push their thinking by presenting the evidence that some people say that the effect of the knot can be explained by length rather than concentration.

CUTTING THE STRING

The knot problem raised difficult questions for many students about what might make a balloon move lower or higher. Some students devised theories about this movement early in their investigation, as did Sally with her anchor theory, and continually struggled to prove this early impression. For example, Holly firmly believed that the balloon would always come to rest on the end of its string. She began her first

experiment with the balloons stating that cutting the balloon's string would not help it rise but would only make it go lower. She couldn't explain this theory and eventually backed down from her assertion after considerable pressure from Jessica to explain why she would say such a thing "since cutting the string would clearly make it rise."

Later she attempted to raise a balloon that was resting on the tip of a string by adding additional string to the bottom, clearly a return to her idea that balloons come to rest at the end of their strings. Surprisingly, Jessica didn't challenge this theory and both girls experimented with this idea until they decided that it was "just too much weight" and wouldn't raise the balloon. Toward the end of their first session with the balloons, however, together they explained the relationship to the balloon of the extra string which they had added onto the original string.

Holly stated that the string lying on the ground is "just excess".

"If there was no floor, the balloon would go up because of the excess weight." explained Jessica.

"Yeah," agrees Holly.

Do you mean that the if the floor was lower the balloon would go down lower?

"No," protests Holly. "It would be higher."

"Yeah," agrees Jessica. "It would spread out more."

So if the floor was lower there would be more room for the string to be suspended.

"Right."

At this point neither student appears to have held onto an understanding of the weight of the string and its relation to the balloon. They both seem to favor the idea that the balloon has a fixed height at which it stays, which they supported in this case with Holly's theory that it comes to rest on the end of its string.

In spite of this agreement about the string resting on its end if the floor was lower, the girls did not agree on what the balloon would do if we cut it just above the floor.

"It will go down," Holly predicted.

"Why do you always say that? You always say that and then you say that you didn't say that." protested Jessica.

After a brief discussion, they both agreed that actually nothing would happen if the string was cut. When the balloon rose, they were both surprised.

"Oh,wow." Jessica exclaimed.

"Well, I guess we were wrong." pondered Holly.

When the balloon later began to drift down, Holly predicted that it was returning to rest about half an inch (the amount cut) above the floor.

"No way," stated Jessica. "It has to rest on the end."

What would happen if we cut off another inch?

"Oh, well then it would go up and come down and be a little higher than it is now."

They are both stumped when the balloon rises and remains on the ceiling.

Their confusion leads them to their best understanding of the relationships between the two interacting factors.

"I think that just a little weight makes a lot of difference," notes Holly. "The ratio of how much air is in the balloon and how much weight is on the string decides whether or not it will stay up or not. It's like half an inch will made a real difference."

What do you mean by the ratio.

"I think that initially the string was heavier because it sunk down and now the air is heavier."

What do mean by heavier air?

"More weight to pull it up." Holly explains.

By "more weight", it seems to us that Holly probably meant "more upward pull" - an idea that is close to adequate. "Weight" then takes on a more general meaning - more akin to force - instead of being limited to the down-pulling force of gravity. She has an idea, and she is using words that she feels comfortable with, in her attempt to express her idea - even at the expense of using these words in an unconventional way. The words do not get in the way of ideas in this case, as they do where they are used to substitute for ideas.

Holly and Jessica leave the problem at this point and never return to this problem, feeling that their explanation is sufficient, in spite of the partial nature of their theories. Other students also seemed satisfied to stop their inquiry once they verbalized some idea of balance, or in this case the inbalance within the system.

Philip and Steve, who chose to explore way that the helium and gravity worked in the balloon system, also worked on why the balloon rose to the ceiling and then later fell. They tried to explain this phenomenon with the idea of gravity.

"It jumps because the helium is going up fast, and then it comes back down when gravity gets hold of it again."

Is there ever a point when the two forces are happening at once?

"Sure," Steve explains. "When it weighs the same. Both things weigh the same; the force going down and the force going up."

"The pressure inside the balloon is the same as the pressure outside the balloon," Philip adds. The helium is the same as the gravity."

As mentioned previously, these students have arrived at some idea of equilibrium in this system, but the time element - both forces acting all the time, whether equally or not - is not clear, nor is it clear just what are the forces which are in equilibrium (of the pressure inside and outside the balloon).

Computers and Students

After an initial interest in the computer simulation model of the balloon, most students chose to focus on the real balloons. The reasons for this choice at least in part were due to the failings of the program. As we mentioned earlier, the qualitative program had a flaw which caused illogical movements by the balloon, and, after the initial experimentation, the quantitative program did not hold the students' attention over the course of the sessions. In addition to these technical aspects of the computer simulation, we noticed from the protocols that the researchers unintentionally offered fewer interventions during the students' exploration at the computer than their experimentation with the real balloons. Although it is unclear as to how this may have affected the students' enthusiasm for the computer, questions posed by the researchers might have provided the students with new dilemmas to be explored.

What the computer did provide was an opportunity to view how the students approached the problem on a computer as compared to the actual balloons. The students' ability to understand the computer simulation varied considerably, as can be seen by the following two examples. In the first example, the students had successfully adjusted the equilibrium of real balloons before they attempted the computer simulation. Their task in this instance was to try to to get the balloon in the

simulation to remain at a constant height when released.

When their first attempt (15cm balloon with 7 strings at 90cm) dropped sharply, they decided to make the balloon larger. The larger balloon (25cm with 7 strings at 95 cm) also dropped.

"So, it's not the centimeters," Eric commented. "Maybe we should add more string."

Although we did not ask which centimeters, it appears that he was referring to the balloon's centimeters. The next attempt included a larger balloon and more string (30 cm balloon with 12 strings at 95 cm) and it still dropped.

"We need more strings!" exclaimed Eric.

Although Eric's logic at this point seems unclear, perhaps he has decided that since increasing the centimeters did not raise the balloon, the strings must be the important variable and, therefore, should be increased. In his work with real balloons, Eric was able to successfully raise and lower the balloon by adding and cutting strings. Either he does not feel that his previous work with balloons is valid for the computer model or he has forgotten about that experiment because he does not seem to be drawing on his knowledge about strings with the real balloons.

The students entered a smaller balloon (15cm) and more strings (32) released at 75 cm. This dropped even more sharply than any previous balloon.

"What now?" asked Sally.

"Just put in anything." Eric mumbled.

Despite these students' successful completion of the initial experiment on real balloons, they found the computer model to be baffling. Although they continued to work with the model, it became a game of typing rather than a thinking exercise and neither of these students was ever able to reach any conclusion about how one would achieve a balloon resting at one spot on the computer.

Another student, Peggy, logged in the balloon data and then waited patiently (through more than 650 units of time) while the screen display computer balloon slowly sank. Her partner, apparently bored with watching the balloon, suggested trying new numbers. Peggy protested claiming that she knew that the balloon would come to rest at 90 centimeters - "the same height as those", referring to the real balloons behind her. (Throughout her session at the computer Peggy talked about the height that she was selecting in feet and then accurately entered the amount in centimeters on the screen, apparently making the calculations in her head.) Her final conclusion about how to achieve a specific height on the computer simulation was to add 30 to the desired height.

"At 90 it dropped at 60, so you start at 60 to get to 30."

Like Eric, Peggy had experimented with real balloons prior to her work on the computer. Although she had been successful in altering the height of the balloon, she seemed to think that the variables of the string and helium were unimportant in the simulation. Instead she chose the balloons' starting height above the floor - a variable she had never considered

with real balloons - as the most salient variable for the computer balloon.

Other students had more success with their computer experiments. Philip and Steve started out with a small balloon (15 cm) with 2 strings at a height of 90 and predicted that it would rise; it dropped.

"Make the balloon bigger, then it will go up." suggests Philip.

Their next balloon (30 cm, 1 string, at 90 cm) rises sharply. They change the strings to 5 and it falls. Their next balloon (40 cm,3 strings, 90 cm high) acts as they predict and rises gently. After additional attempts they are able to get different sized balloons to remain level. When asked how they figured out what would make the balloon act this way, Steve's response was that he couldn't say, he just felt it. Although they were never able to explain how they were able to make accurate predictions, they had found a formula that worked and were willing to repeat it rather than explore why it worked. It is interesting to note here that these same students created a theory about the real balloon system around the word gravity but were unable to explain what that word meant.

In one instance the computer did present a problem for the students which they explored and eventually solved with the real balloons. While at the computer, they began to wonder why they had to choose a height from which to release the

balloon. After working for a time with the quantitative version of the program, they changed the number of strings and made small adjustments to the height of release. In these instances one student, Sara, made continuous comments about her confusion of what height has to do with whether or not the balloon falls or rises. As reported above, she and the other group members eventually resolved this question to their satisfaction through experiments on the real balloon.

Students' Comments about the Computer

In spite of the fact that students were free to work with either the real balloons or the computer simulation, all students spent more time on the real balloons than on the computer. When asked about the computer program, however, the students' comments were confusing. Two girls joined forces to explain their reaction to the computer. "It's easier to try," said one. "But harder to figure out," added her friend and they both nodded. When questioned about that comment, a third student replied that "It's only a computer and not the real thing. You can't cut the string or move the strings around like you want to. I guess I just like the real thing."

A different set of students (Peggy, Sally, and Rita) thought that the computer was "cool" and "awesome". Peggy expanded that definition. "You can try different things real quickly to see what will happen: the results are quick."

Unlike Heather and Lori or the group above, this group stated that they preferred working on the computer and found it "slightly" more fun - although they too spent the vast majority of their time on the real balloons. Peggy continued.

"You know this (the computer) will have the right answer. (By contrast) we're just guessing."

"The computer's easier to figure out than the balloon. Better than doing it yourself. With the balloons we had to sit there and work it out ourselves." added Rita.

"Yeah," agreed Peggy.

"More work. We're lazy" laughs Sally.

What these students consider to be the nature of the task deserves comment here. It appears that what is easier with the computer is getting it to do what they want; or perhaps even simply finding out, dependably, what it does in given circumstances. There is no reference to the job of trying to understand what is going on.

During this conversation, these students also talked about the more mysterious aspects of the machine.

"It knows what's going to happen. Hey, how does the computer know what is going to happen?" Rita asked.

"Well, it's a computer, so....! It's what computers do." offered Sally. "See that little disk that's in there?"

"Yeah, but somebody programmed that little disk." Peggy reminded.

"I know." Sally frowned.

"So the person who programmed that disk," continued Peggy.

"had to try out all these things before they could program it."

"Because they're brains!" exclaimed Sally.

Is that what you meant by knowing how to do all the stuff?

"No," Rita said. "It's ...I don't know... I just.... I don't know..... It's weird."

This same group was unperturbed when they encountered the program error in the first model which allowed a large balloon with large strings to go up from the ceiling, down from the table, and up through the ceiling from the floor. Sally expressed surprise when this happened ("Oh come on!"); however, when asked why the balloon went up from the ceiling and floor and not from the table, she laughed "Because it doesn't like Peggy" and made no further comment about the computer's discrepency.

CONCLUSION

In this study, we set out to explore the various ways that young adolescents understand and explore complex systems and to begin to investigate the role of situations. Our detailed studies of small groups of students allowed us a good understanding of a number of different ways in which the students developed their ideas about the balloon system. On the other hand, the small sample and technical flaws in one computer program make it premature to make comparisons across ages, or between real life systems and simulated systems. Rather than conclusions on these areas, we will raise a number of questions.

One difference which characterized Air and Tina in contrast to the other students was the effectiveness of their experimentation. Schauble and Glaser have pointed out the interaction between the degree of adequacy of youngsters' notions about a phenomenon and the degree of adequacy of their means of experimenting to check out their ideas. This is amply demonstrated in these protocols. Air and Tina were able to keep clear in their minds which aspect they wanted to work on at a given moment and created experiments which would shed light on that particular aspect. They followed through the implications of one finding checking it out in true hypothetical-deductive fashion - if y is true then x should be true, let's try x. This approach was noticably missing from

the protocols of the younger students, its absence most dramatic during the computer experiments where these students focused on the numbers on the screen rather than what those numbers represented.

It may seem contradictory but this ability to keep focusing on one thing one focus at a time goes hand in hand with an ability to develop an all encompassing theory about the phenomena. Kim and Tina aimed for a simple understanding into which they could fit all the pieces. The other students saw the different problems as unrelated to each other, even while they were unable to keep them from influencing each other.

The inability to work with the interrelatedness of the ideas - the very essence of understanding a complex system - is manifested in the students' ideas themselves. Kim and Tina developed ideas of forces working against each other. The younger students had more static ideas: balloons have fixed heights where they would stay even if the floor were dropped; they have fixed tendencies to rise either up or down: whether they are in real life or on screen, they stop at one same height. This static view of the phenomena is reminiscent of Aristotelian views. To the extent to which younger students moved toward a transitional understanding closer to Kim and Tina's, they moved away from such static views. Philip and Steve are the clearest example of this transitional. Although they talked of forces acting in opposite directions, their view of the state of the

system was determined first by one force then another, and not by the two acting simultaneously.

Additionally, we found that a student's choice of scientific-sounding words often revealed a great deal about that student's understanding and may have affected the student's inquiry. Billy-Jo avoided these types of words altogether claiming that they were unclear; Molly stretched the definition of familiar words to represent new ideas; Philip continually used scientific-sounding words, which he could not define, to explain puzzling phenomena. In Philip's case, the use of words such as "gravity" or "pressure" masked his struggle and misled fellow students into thinking that, unlike them, he understood what was happening. In contrast, Billy-Jo, who refused to use scientific-sounding words - or to let others explain what was happening by using such words - was able to reach a satisfactory understanding about her question of why balloons behave differently when released at different heights. Molly's lack of familiarity with the appropriate words which describe the upward force of the balloon system did not prevent her from exploring this new idea; she simply expanded the definition of a familiar word.

We were able to see all of the details of the students' ideas because we watched them discover their own ways of trying to figure out what was going on rather than guiding them to the "correct" understanding. In one instance, a student seemed to understand both the struggle and the value

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of this way of learning. Billy-Jo had become frustrated with her inability to understand the balloon system, although she couldn't articulate a specific question that she was trying to answer. She turned to a researcher and stated that she wanted "the answer." The researcher asked her what exactly she wanted - a word or to really understand what was going on. She thought about that for a few moments and then looked directly at the researcher and quietly stated, "what I want is to really understand it." Both she and the researcher agreed that this might take a while and together they looked at what questions were most troublesome for Billy-Jo. We believe that the depth of any student's understanding is greater when s/he is able to proceed to an answer by developing his/her own questions. In these cases a word or definition is not an adequate substitute, and in some instances may actually stop rather than assist a student's understanding.

On the basis of such a small sample, it is impossible to reach firm conclusions. However, the findings presented here address several issues related to teaching complex systems. Our study raises questions as to whether or not students in the early years of high school are able to develop an adequate understanding of the interrelationships of a complex system.

Our computer simulations raised several other questions. Why did the simulations, which presented three variables of the system in a simplified form, seem so difficult? Is it something

about this particular form of simulation or is it related to the actual complexity of the system being simulated? Might it be important to include in any simulation a way for students to experiment with widely held, if incorrect, theories?

Finally, we feel that this study presents an appreciation for the extensive time and effort that is involved in a basic shift in one's understanding. We realize that the researchers' approach to uncovering the students' spontaneous understanding in which one works with small groups of students over a period of time is very different from the way that most teachers by necessity cover material in their classrooms. More study of students' naive understanding of complex systems, as well as of pedagogical approaches, is necessary.

We believe that all of the above questions are worthy of careful consideration by both researchers and practitioners. We hope that they will serve as springboards for the exploration of the nature of the teaching of complex systems.

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